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13. ABSTRACT

The Symposium on Biodynamics Models and Their Applications took place in Dayton, Ohio, on 26-28 October 1970 under the sponsorship of the National Academy of Sciences - National Research Council, Committee on Hearing, Bioacoustics, and Biomechanics; the National Aeronautics and Space Administration; and the Aerospace Medical Research Laboratory, Aerospace Medical Division, United States Air Force. Most technical areas discussed included application of biodynamic models for the establishment of environmental exposure limits, models for interpretation of animal, dummy, and operational experiments, mechanical characterization of living tissue and isolated organs, models to describe man's response to impact, blast, and acoustic energy, and performance in biodynamic environments.

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BIODYNAMIC MODELING AND SCALING: ANTHROPOMORPHIC DUMMIES, ANIMALS AND MAN

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ABSTRACT

After a brief outline of the applications and methods of biomechanics and the major sources of biodynamics data, this paper reviews the status of mathematical modeling, physical modeling (dummies) and scaling of models and damage levels.

Biomechanics data required for preparing mathematical models, as well as for adjusting and validating the computer programs, are found to be insufficient for computational applications. Because of this paucity of supporting data, computer models are in general oversimplified and rudimentary, despite the availability of adequate computational techniques used in the aerospace industry.

Physical models and the requirements for dynamic similarity are discussed. Although quantitative simulation is warranted under some circumstances, anthropomorphic dummies are expected to be of most value as visual aids and for purposes of demonstrating kinematic relationships between man and vehicle.

Scaling from dummies to man and from animals to man is difficult to justify theoretically because of differences in structure, size and modes of failure. However, damage scaling in terms of the inputs (G and delta-V) required for failure, is shown to be accurate enough for purposes of rough approximation.

The mathematical model approach, with proper validation, is concluded to offer ultimately the greatest promise of accurate quantitative prediction.

INTRODUCTION

Biomechanics is an interdisciplinary blending of the biomedical and the physical sciences applied to the effects of dynamic mechanical environments on living organisms. In its broadest terms, biomechanics covers a wide range of mechanical environments such as shock and vibration, acoustic inputs, air blast, underwater explosion effects, etc.; as well as applications to a variety of organisms. The discussions of this paper are restricted to the narrower subject of the effects of whole body impact or deceleration (not direct impact of projectiles, etc.) on man and other animals.

The primary purpose of biomechanics is to predict response and injury, via the following route:

(1) Input - Definition of the force application or input to the biological system, spatially and in terms of its time history. In many cases the loading system is coupled to the biomechanical system, for example in the cases of vehicular crashes, and it may become necessary to define inputs to the entire vehicle-man coupled system.

(2) Response - Observation, analysis or prediction of the response of the organism to the inputs. In the cases of analysis and prediction, it is necessary to obtain some kind of biomechanical definition, or model, of the organism and to subject this model to the mechanical inputs.

(3) Failure - Observation, analysis or prediction of failure, damage, or injury to the organism. For purposes of prediction, it becomes necessary to determine the various mechanisms of injury and to ascertain whether one or more mechanisms have been excited to the point of failure.

(4) Prediction - Prediction of response and failure of the animal, or another animal, to other inputs.

The latter three steps are discussed further in this paper in terms of the methods employed, an evaluation of accomplishments to date, and recommendations for the future.

METHODS OF BIOMECHANICS

Four broad sources of data are employed to assist in the process of prediction human response and injury:

(1) Results of experimentation on man and natural incidents involving humans.

(2) Animal experimentation.

(3) Mathematical "experiments" with computer models.

(4) Physical experimentation with dummies.

Table 1 presents in capsule form the relative advantages and disadvantages of each approach to obtaining useful data.

The above listing of methods of obtaining data is generally in the direction of less direct applicability to man (requiring more adjustment, interpretation, or scaling) for numbers (2), (3), and (4), although their sequence is not intended to be exact. Mathematical and physical models are discussed below in terms of the sources of inaccuracy and methods of application.

MATHEMATICAL MODELING

The process of mathematical modeling of the human body may be compared directly with the similar process employed in the aerospace industry to model a large aircraft or space structure. Table 2 lists the main steps required to develop and validate a mathematical model.

Although the aerospace industry has matured and developed a sophisticated technology of mathematical modeling, the biomechanics community has not been able to justify complex models (because of the paucity of the biomechanical data required for modeling and validation of models) and only very recently has begun to adopt aerospace methods. The best work has been done in the biomedical areas (1) and (3) of Table 2, but the potentialities of the engineering areas (2) and (4) have not been exploited well.

METHOD	ADVANTAGES	LIMITATIONS
MAN: Experimentation, results of accidents	Realistic: • Material properties • Neuromuscular reactions • Injury modes	• Experimentation only to point of discomfort • Accident details hard to reconstruct • Accident data statistical
ANIMALS: Experimentation	• Tissue properties similar to man • Neuromuscular reactions • Injury modes similar to man	• Structures different from man • Organic differences • Size scaling necessary
COMPUTER MODELS	• Ease of "experimentation" • Programs reproducible and permanent • Model may be improved to any degree of fidelity	• Parameters must be adjusted per experiment results. • Need a good set of subsystem (organs, etc.) models for good overall system model
PHYSICAL MODELS: Anthropomorphic dummies	• A superb visual aid • Inexpensive way of observing kinematic effects	• Expensive to model internal organs adequately. • Serious problems of friction damping, mat'l properties • Injury hard to predict

Table 1

STEP	AEROSPACE MODELING	BIODYNAMIC MODELING
(1) Idealization of actual structure into lumped parameters or continuous element in order to prepare the subsystem models.	Reduction of beams, plates, shells, etc. to mass-spring elements. Nonlinearities, large deflection effects, and damping estimated.	Tissue properties, joint properties, organic geometry must be reduced to lumped or distributed elements. Nonlinearities, damping estimated.
(2) Subsystems are coupled to form a system model	The math modeler's skill enters here in developing an efficient (short running time) system model. Coupling techniques are discussed in the text.	
(3) Model exercised to obtain modes, frequencies response, and failure	Failure defined in terms of excessive deflection (performance affected) or permanent strain.	Failure criteria include strain (fracture, rupture) deflection (cervical stretch, for example), pressure (a concussion mechanism).
(4) Model adjusted and validated by comparison with subsystem and system tests.	Comparison of free-free modes and frequencies, static deflection tests, influence coefficients[3]	Modes, frequencies[1], impedance measurements[2] from vibration and low-level impact tests.

Table 2

Much work has been done to define tissue and joint properties. Without tabulating the actual properties, Table 3 lists some sources and examples of the data available. Data of this kind must be available in order to accomplish Step (1) of Table 2.

Step (2) of Table 2 involves formation of the system model, which may be one or more organs, the entire body, the body plus restraints, etc., depending on the application to be simulated. The human body is a structurally complex system, composed of subsystems (organs, limbs, etc.) made of dissimilar materials and coupled to each other in complex ways. In certain loading regimes such as high frequency vibrations, grossly different transmission properties of the bony skeleton and the "hydraulic" vascular system will result in parallel structural systems responding out of phase, but coupled throughout by interconnecting tissues. With lower frequency inputs, however, the parallel systems may react essentially as one system. Modeling such a system poses formidable challenges to the structural dynamics analyst who is accustomed to modeling aerospace structures. He must learn to select the significant breakdowns of mass, elasticity and damping in order to construct the biodynamic model; and the selection techniques will be somewhat different from those he has used for steel or titanium in plates, shells, I beams, etc. However, the general methods of analysis are identical, and the aerospace industry can provide a powerful tool for computer modeling the complex human structure.

Hurty[16], Bamford[17] and others develop a most fruitful method for computer modeling of exceedingly complex structures. In the component mode approach to modeling, the subsystems are first broken down to whatever level of detail is required for adequate dynamic representation. Experience and judgment are, of course, required to determine adequacy. Besides, however, the subsystem may be tested experimentally to ascertain whether enough modes have been represented, and how accurately. There may, of course, turn out to be a limitation in computer capacity or running time, which could force the modeler to split the subsystem into smaller

TISSUE, JOINT, ORGAN	SOURCE OF DATA
Soft tissues, muscle, bone	Goldman & von Gierke[4], Nickerson & Drazic[5], von Gierke[6], Fung[7], Starr et al[8], Sittel[9], Roberts et al (ref)[14]
Blood, arteries	Fung[7], Roberts et al (ref)[14], Starr et al[8]
Intervertebral disc	Hanzel[10], Sonnerup[11], Orne & Liu (ref)[13]
Spine	Henzel[10], Orne & Liu (ref)[13]
Knee joint	Edwards[12]
Leg, foot	Hirsch & White[15], Roberts et al[14]
Skull	Goldman & von Gierke[4], Starr et al[8]

Table 3

subsystems. However, with a large machine which can handle of the order of 100 elements comfortably, it should be possible to develop good dynamic lumped models of each human organ as a subsystem. The subsystem program is then run to obtain output modes. Subsystems are now tied together at their physical points of connection to obtain overall system response to a set of inputs. The final step is to go back to each subsystem to read out its response (perhaps to failure) in its own modes.

The basic advantage of working in modal coordinates is economy. The overall coupled system modes are approximately equal to the number of subsystems times the modes represented in each subsystem. Therefore if an average of 10 modes were found adequate to represent each of 10 different subsystems, the coupled system program would have 100 elements. A single program for all subsystems taken together could have required 1,000 elements, which would have been prohibitive in size. Therefore the component mode approach appears suitable for modeling the human body, with its hundreds of bones and muscles.

A comment is in order on the question of continuum mechanics programs vs. lumped parameter programs. There is really no difference between these approaches if a fine enough breakdown of lumped parameters is made. Stress wave behavior <u>will</u> be exhibited without an inordinate degree of definition. A beam or column, for example, will require of the order of 10 subdivisions to exhibit minimum "continuous" properties.

Nonlinearities do pose a special problem in the component mode approach, since the modes will shift with change in amplitude of input and response. For example, it is known that a steady linear acceleration will cause increased stiffness, less damping, and higher energy transmission to internal organs when the human body is then subjected to vibration. It is therefore necessary to adjust the subsystem modes to be consistent with the response obtained, and this will be somewhat of an iterative process.

After the computer model has been assembled and exercised (step 3 of Table 2), it is desirable to make adjustments at all levels possible within the system. Test data[1, 2, 3] on modes, frequencies, etc. should be used to validate and adjust the subsystem programs. Table 4 presents some data on first mode frequencies.

Besides response data, static and dynamic failure data should be employed to validate computer models. (Some of these data will be presented below in a discussion of damage scaling). The end product is an adjusted and validated computer program which should provide some predictive value when applied to a situation for which experimental data do not exist.

How well has the biomechanics rationale described above been applied to the human body subjected to impact? The answer is, generally, in a rudimentary and perfunctory fashion. A fair (but not complete) picture of the history of computer models applied to human impact is presented in Table 5, in chronological order.

The earlier models were oversimplified one-or-two degree of freedom models, and they had limited predictive value. Some recent models (Turnbow, McHenry and Naab) treated the man as a kinematic linkage without internal flexibility, so that only external (to the body) loads could be determined. Other more detailed models (Coermann, Starr) were still not fine enough in breakdown to yield significant load and failure results within the human body. Only the most recent work of Orne and Liu[13] appears to have sufficient detail to be a truly significant tool for predicting spinal response and failure. Unfortunately, their model does not appear to have been adjusted by comparison with experiment, and validation of its predictive utility remains to be demonstrated.

To summarize the state of the art, it appears that only this year has an (apparently) adequate model of the human spine been developed. Obviously, much work remains in developing adequate models of the other human subsystems (limbs, organs, etc.), and coupling them to finally obtain a good system model of the human body.

MODE	FREQUENCY, CPS	SOURCE
Human viscera	3, 4	Coermann et al[2], Roberts et al[14]
Standing man	5.7, 10	Stech & Payne[20], Hirsch[18]
Seated man	6	Stech & Payne[20], Hirsch[18]
Supine man	7.4-9.7	Stech & Payne[20]
Skull	700	Goldman & von Gierke[4]
Spine and head	6	Terry & Roberts[19], Stech & Payne[20]
Thorax-abdomen (pressure excit.)	45-60	von Gierke[6]

Table 4

YEAR	MODEL	ELEMENTS IN COMPUTER PROGRAM	INVESTIGATOR	CORRELATION WITH EXPERIMENT
1941, 1943	Fluid-filled rigid skull		Anzelius, Goggio[14]	
1957	Man-seat	Two	Latham[19]	Seat load only
1958	Head on spine	Continuous elastic rod	Hess & Lombard[19]	Good, head accel.
1958	Supine man	One	Kornhauser[26]	Good, survival only
1960	Standing man	6 masses, 7 springs	Coermann et al[4]	Good, vibrations
1962, 3	Head	Lumped, continuous	Payne[14]	
1966	Head on spine	One mass, continuous	Liu & Murray[23]	None
1966	Seated man	8 masses (kinematics only), spring restraint	McHenry & Naab[14]	Good, seat loads only
1967	Man-seat	"	Turnbow et al[21]	"
1968	Skull-brain	10 elements	Starr et al[8]	Qualitative only
1968	Head on spine	Cont. viscoelastic rod	Terry & Roberts[19]	Good, head accel.
1969	Head on spine	One mass, continuous	Liu[25]	None
1969	Seated man	One, two	Yeager et al[24]	Good, seat loads
1970	Fluid-filled elastic skull	Continuous	Benedict[22]	None
1970	Head on spine	25, 3 degrees of freedom	Orne & Liu[13]	None

Table 5

PHYSICAL MODELING AND SCALING

Table 1 summarizes the major advantages and limitations of using dummies as biodynamic tools, and these will not be expanded in more detail. Further, although it would be useful to discuss the practical problems of material selection (physical simulation of properties) and model construction (friction in joints, etc.), the present discussion will be restricted to the questions of scaling "laws" and what they predict about the adequacy of dummies and animals to represent the human body.

Hudson[27] presents a rather thorough discussion of scale model principles, although he does not address the special problems of anthropomorphic dummies. It is not appropriate to present here the theory of dimensional analysis and dynamic similarity. Instead, the conclusions reached by Hudson and others on the conditions required for dynamic similarity are presented in Table 6.

For dynamic similarity in general, it appears that geometric similarity and identical material properties are required. Hudson, however, indicates some structures for which complete geometric similarity is not required and for which all material properties need not be identical. Likewise, Baker and Westine[30] and Horowitz and Nevill[31] discuss modeling with dissimilar materials, although the former require materials with similar stress-strain curves while the latter use the area under the stress-strain as the correction criterion. Thus it appears possible to justify relaxation of the requirements for dynamic similarity under special circumstances.

Since humans and other animals are exceedingly complex structures, it is not possible to justify simulation by dummies on any theoretical basis. Only under very restrictive conditions, as for example when using kinematic dummies (no flexibilities, but simply masses and linkages with correct moments of inertia) to find motions and loads on restraint systems, can physical models serve useful quantitative purposes. As tools for purposes of visualization, or for demonstrating kinematic relationships of human and vehicle dynamics, anthropomorphic dummies are very helpful.

SOURCE	STRUCTURE	REQUIREMENTS FOR DYNAMIC SIMILARITY
Hermes[28]	Beams Plates Frames	(1) Geometric similarity, boundary conditions same (2) Velocity/speed of sound in mat'l = constant (3) Young's modulus of proto. & model must be same (4) Poisson's ratio " " " " " " "
Heller[29]	Armor, non-penetrating impacts	(1) Geometric similitude (2) Identical material (3) Equal impact velocities
Hudson[27]	Beam	Area/length^2 = constant, radius of gyration/length = constant (rather than complete geometric similarity).
	Plate	Geometric similarity, Poisson's ratio the same

Table 6

The scaling difficulties mentioned above apply, of course, to animal-to-human comparisons. Structure and size differences present serious obstacles to quantitative scaling. However, as with dummies, animal experimentation is invaluable in uncovering responses and failure mechanisms which often suggest similar qualitative behavior of human.

An invaluable animal-to-man correlation approach is to work with non-human primates of similar construction and to scale directly to man. This approach, of course, allows experimentation with primates which would not be permitted with humans. Besides this direct scaling for clinical purposes, the primate-series experimentation offers exciting possibilities for measuring tissue and organ properties and responses required for developing and validating computer models, which models may later be scaled for applications to humans.

DAMAGE SCALING

Despite the differences in structure which precludes any rationale for scaling between animals and man, it has been possible to do some fairly successful scaling based on the inputs required to produce damage. This is even more surprising when one considers the different modes of failure possible with any animal and man. Table 7 presents some modes of damage and the inputs required to produce them.

The two main input parameters found most useful for scaling purposes are acceleration level, or number of g's, and velocity change, delta-v. There exists a background of structural dynamics technology (see, for example, Kornhauser[42]) which presents the rationale for employing these two parameters to characterize the input shock, even though some not-quite-second-order effects are omitted (rise time, pulse shape, etc.), and the two parameters do indeed prove useful in presenting animal survival data. Kornhauser and Gold[43] show the following very approximate scaling laws for a wide range of animal sizes:

$$G \cong 40/L \qquad \text{Eq. (1)}$$

MODE OF FAILURE	LOAD, LBS.	ACCEL., g	DELTA-V, fps	P, psi	SOURCE OF DATA
Standing man (leg)	1,600	20	10		Hirsch[18]
" , voluntary		10	10		Swearingen et al[32]
Seated man (vertebrae)	1,400	10-30	13-26		Hirsch[18]
" , voluntary		10	15		Swearingen et al[32]
Supine man (?)		20	53(50%)		Stech & Payne[20]
Squatting man, voluntary		5	25		Swearingen et al[32]
Head, lateral (brain?)		50	15.4 (21 with helmet) *		Hirsch[34]
" " , voluntary		38	6.5		Lombard et al[33]
Concussion (?)		-	15-25		Rayne & Maslen[35]
" , intracranial pressure				18-40	Gurdjian et al[36]
" , " " , dogs				25-95	Gurdjian et al[37]
" , cervical stretch					von Gierke[38]
Skull fracture			14-20		Lissner[39]
" " , flat	600 in-lbs.		~17		Goldman & Von Gierke[4]
" " , 90^{o} corner	60 in-lbs.		~ 6		Goldman & Von Gierke[4]
Ribs, lungs, diaphragm, heart					Evans & Patrick[40]
Aorta, rupture					Starr et al[8]
Hydraulic effects					Payne[41]

* There would appear to be a discrepancy between this and the 53 fps for the supine man, unless the lateral head damage really reflects the mode of cervical stretch which does not occur in the case of supine, whole body impact.

Table 7

where L is a characteristic length (in feet) in the direction of acceleration, and

$$27 < \text{delta v} < 53 \text{ fps} \qquad \text{Eq. (2)}$$

for all animals tested to date.

The first scaling law makes sense if animal tissues have approximately equal densities and strengths. If the tissues behave as fluids with the density of water, then the pressure produced by 1 g of acceleration is equal to about 1/2 psi per foot of "depth". Equation (1) above would then be equivalent to the statement that animal structures can withstand about 20 psi of pressure, induced by inertia loading of the tissues.

The second law shows the relative invariance of the delta-v required to produce injury, over a wide variety of animals from mice to men. At first glance this is most surprising, because of differences in size and structure. However, size in itself may be explained away, since Kornhauser[42] shows that delta-v is almost constant for uniform beams of any size, with small variations to account for different boundary conditions or methods of support. Structural differences, unfortunately, are not that easy to rationalize since beams and shells with concentrated masses may have much lower delta-v for failure than uniform beams.

Despite structural differences, there is a mechanism for explaining why animal delta-v's are not too different; namely, Darwinian natural selection. Land animals live in an environment which produces falls from various heights, and impact tolerance should be a definite factor in survivability and natural selection. By this token, of course, the tree-dwelling creatures would be expected to survive higher delta-v's than surface dwellers. To test this hypothesis, Table 8 separates various animals into these two groups. Some correlation does show, but not enough to be conclusive. Perhaps some impact testing of fish would reveal whether or not Darwinian selection has had much to do with the existing delta-v tolerances of animals.

SURFACE ANIMALS	Delta-v, LD_{50}	CLIMBING ANIMALS	Delta-v, LD_{50}
Mice[43]	39	Man[20]	53
Rats[43]	44	Rhesus monkey[44]	40
Guinea Pigs[43]	31	Squirrel monkey[44]	48
Rabbits[43]	32	Avg.	47
Avg.	36		

Table 8

CONCLUSIONS

(1) Because of the paucity of biomechanical data required for modeling and validation of analytical models and for definition of failure points, biomechanical models have been rudimentary. Sophisticated computer modeling techniques are available, however, for modeling the most complex biological systems.

(2) Scaling of anthropomorphic dummy data is seldom justifiable on a theoretical basis, but some quantitative results of a kinematic (rather than deformational) nature may be obtained. Dummy experimentation is therefore of greatest value in producing kinematic data as well as qualitative data.

(3) Animal-to-man scaling is most fruitful with primates, and this suggests the value of developing and validating primate computer models in order to help in validating the human analytical models.

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